Transport of Optically Active Particles from the Surface Mixed Layer

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LONG-TERM GOALS

To determine the mass balance of optically-active particles within the surface boundary layer and to identify processes responsible for their redistribution.

OBJECTIVES

1) Perform manipulative experiments in which a known quantity of optically-active $CaCO_3$ particles are introduced into the surface mixed layer, and tracked over time and space. This approach effectively removes uncertainty in the production term of the mass balance equation.

2) Quantify the relevant physical and biological loss terms that remove optically-active particles from the mixed layer (vertical mixing, sinking of discrete particles, particle aggregation, dissolution, and grazing-related repackaging of particles into fecal pellets).

APPROACH

The focus of the Chalk-Ex project is a sequence of multidisciplinary field experiments wherein patches of optically active particles were created within the mixed layer by dispersal of Cretaceous chalk ($CaCO_3$) from the stern of a research ship. Two deployments were done during each of two cruises: November 2001 and June 2003. Each deployment used ~13 tons of chalk to produce a patch of approximately 2 square km. The first deployment of each cruise was made at a eutrophic site within the Gulf of Maine (hereinafter referred to as the "north site"). The second deployment was at a mesotrophic site along the continental slope to the south of Georges Bank (the "south site"). Patch evolution was determined from a combination of time series and spatial survey measurements over periods of 2-4 days. Associated with the chalk deployments and optical surveys (Balch), were Lagrangian and hydrographic drifter deployments (Plueddemann), drifting sediment trap deployments and determination of particulate export (Pilskaln) and measurements of grazing and aggregation from in-situ samples (Dam/McManus).

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WORK COMPLETED

Optical measurements- Balch

Surface underway optical measurements of attenuation, absorption, scattering and backscattering were made during wagon-wheel and radiator surveys. Water-leaving radiance and downwelling irradiance (for calculating remote sensing reflectance) were measured from the bow of the *r/v Endeavor* using a Satlantic SeaWiFS Aircraft Simulator (SAS). A towed, undulating Scan-Fish with Wet-Labs ECO-VSF attached, allowed real-time mapping of the patch. Free-fall vertical profiles of spectral downwelling and upwelling radiance were made using a Satlantic radiance profiler which allowed high-resolution estimation of diffuse attenuation coefficients. For vertical profile stations, discrete water samples were taken with a rosette sampler, at 6-8 depths within and below the mixed layer. Subsamples were filtered for suspended $CaCO_3$ analyses (Fernández et al., 1993), plus the total and acid-labile backscattering of these samples was measured. The loss of backscattering following a lowering of the pH to 5.8, is well-correlated to the suspended calcite and allowed us to validate the laboratory calibration at sea. A tethered surveillance balloon, with video recorder suspended beneath, was launched after chalk deployment in order to determine the aerial distribution and physical attributes of the chalk patch. The balloon was typically raised to ~190m above the ship, trailing ~360m aft.

Sediment Trap Program and Particle Fluxes- Pilskaln

In order to quantify the vertical export below the patch of Cretaceous chalk (due to biological and/or physical aggregation of the chalk particles), VERTEX-style MultiPIT drifting sediment traps (Knap, 1993; Knauer et al., 1979) were deployed just below the base of the mixed layer within and outside each patch. MultiPIT trap "crosses" consisting of 8 collection tubes, were attached to a drifter mooring inside each patch. Outside the patch during the November cruise, we deployed a drifting sediment trap array with one MultiPIT trap cross located at the same depth as the trap cross within the patch. Following the deployment of the un-instrumented surface drifter into the patch and a rough determination of the surface drift, we deployed the inside-patch trap array and tracked it for 2 days. Of the trap crosses on each array, four trap tubes were designated for stable isotope analyses. Cretaceous chalk has a unique del-^{18}O signature relative to modern planktonic carbonates that makes it easy to trace in the water column and it provided us with the means to verify that collected material in the traps originated from the patch. The second set of four trap tubes (per drifting array, inside and outside the patches) were designated for microscopic and geochemical analyses. During the June ’03 cruise, we deployed both traps within each patch, due to the fact that the outside patch drifter could not be considered an absolute control (due to spatial differences). Moreover, it allowed us to double the amount of material collected, and provided replication within the patch.

RESULTS

Describe meaningful technical results achieved in the report fiscal year. Make the significance clear. Emphasize what was learned, not what was done. This should be a summary of significant results and conclusions, and, especially, any “new capabilities” generated.

The November ’01 chalk patch at the north site was mixed into the top 70m almost as fast as it was added to the surface water. While the increase in backscattering was measurable, it rapidly decreased to background levels and was impossible to locate with either the Scan-Fish or with surface sampling within several hours of deployment. At the south site, there was more stratification and the chalk was detectable for several days. The south site patch was associated with a well-defined "injection" density, and could later be found within +/-0.05 sigma-theta units of the original density (Fig. 1). The drifter that best followed the patch was the sediment trap drifter, drogued to the top 10m. Dispersion of the chalk between the hydrographic drifter, Lagrangian drifters, and sediment trap drifters illustrated the mixed layer shear. The first 40 hours after chalk injection were characterized by weak winds (3-5 m/s) and net heating (60 W/m2). During this period the upper 40 m of the water column restratified, primarily due to horizontal advection. We were able to account for all the chalk within the first 6h after the patch was dispersed, but the measurable chalk decreased exponentially over time, at a mass-specific rate of $-0.15\ h^{-1}$. Optical patch definition using light scattering results and above-water radiance measurements were in good agreement. Based on stable isotope and microscopic analyses of the collected trap material, we concluded that no appreciable amount of the chalk settled into the sediment traps. Similar mass sinking fluxes of $CaCO_3$ and organic carbon were collected by the inside-patch and outside-patch traps. The total particle mass flux outside the patch was slightly higher than that measured inside the patch but the difference was not significant. Trap samples consisted primarily of planktonic foraminifera and pteropod tests as well as crustacean zooplankton fecal pellets and amorphous organic matter. Stable isotope analyses ($\delta^{18}O$) of the trapped detrital material, from which planktonic forams and pteropods were removed, revealed a slightly depleted but relatively strong, planktonic calcite signature, not the highly depleted value typical of Cretaceous chalk.

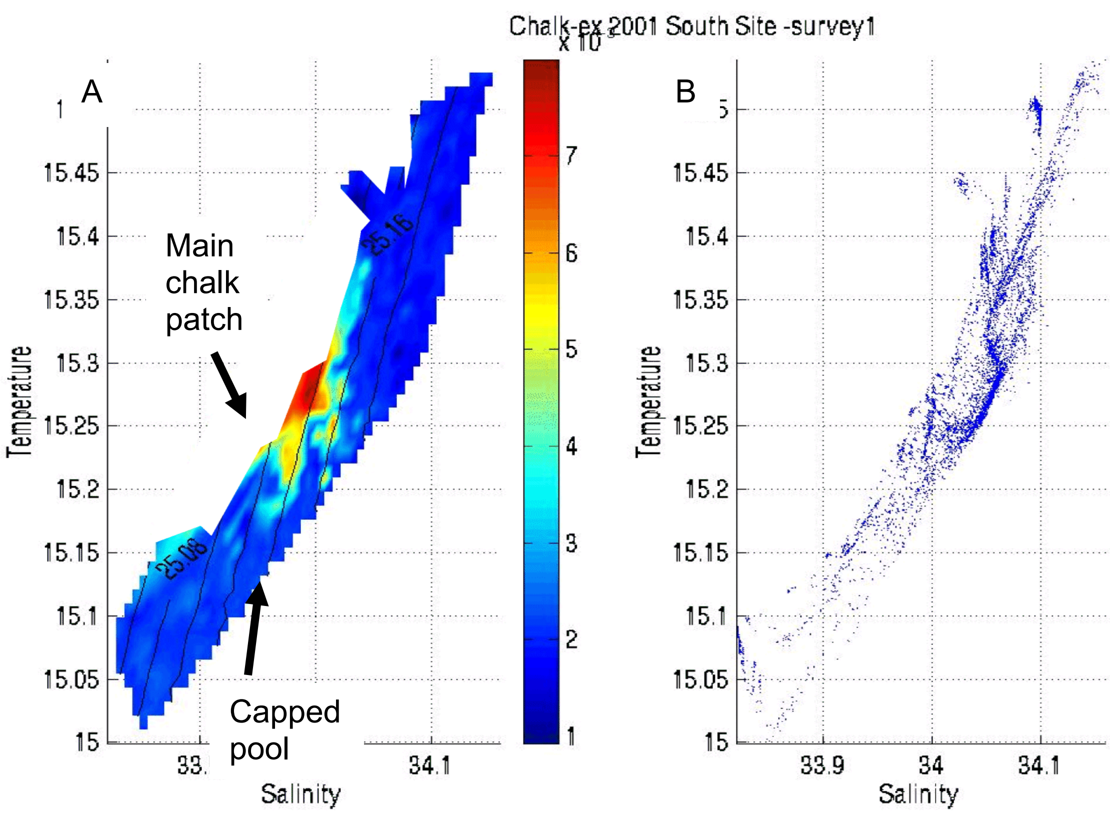


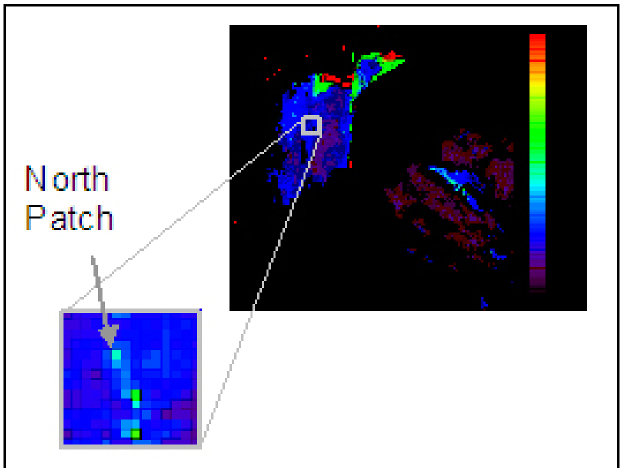
Figure 1. November '01 south site chalk patc, results from Scan Fish wagon-wheel survey. A)Temperature-salinity plot showing intensity of optical backscattering at 532nm (see color scale on right of plot). Isopycnal lines shown in black. Results demonstrate main body of chalk was associated with the 25.14 isopycnal surface and a capped pool was injected at the 25.16 isopycnal surface. B) Distribution of data points used to make panel A.

These results, coupled with the lack of chalk-containing fecal pellets and/or chalk-containing organic aggregates in the traps, indicates that biogenic and/or physical aggregation of chalk particles were *not* important mechanisms contributing to the fate of the chalk particles during the November '01 experiment. This, combined with the minimal chalk grazing by macrozooplankton and measurable grazing by microzooplankton, suggests a potential microzooplankton sink for the chalk.

A fascinating result from the November '01 experiment was the observation of a "hole" in the distribution of chromophoric dissolved organic matter (cDOM; based on continuous measurements of $a_{g\ 412}$) in regions of high chalk concentrations. Reduced $a_{g\ 412}$ plus the size spectrum data of the sub-micron particles (as measured with Flow Field Fractionation), suggests in situ adsorption of the cDOM onto the chalk. Such an observation is not without precedent, but the magnitude of this effect was certainly unexpected.

During the June'03 deployment, intense stratification contained the chalk in the top 15m at both sites, such that the chalk signal was detectable for at least 48h. Unfortunately, neither of the patches was observed by MODIS-Terra due to morning cloudiness, but thanks to afternoon clearing, both were observed by MODIS-Aqua (Fig. 2). Aerial video images from the tethered balloon provided good resolution viewing of the patch at the south site (at the North site, the sun angle was too low for good images by the time the balloon was sent aloft). The results from our June '03 cruise buttressed the results from the November '01 cruise; that is, we demonstrated the importance of physical processes in controlling the chalk distribution.

While much data remains to be worked up, some preliminary observations are in order. Both patches were detectable for at least 2 days following dispersion. Subsequent work-up of the data may show this period to be conservative. The chalk quickly became associated with frontal boundaries, as evident during the Scanfish surveys. We will be looking for evidence of subduction, as observed during the November '01 work. There were significant populations of zooplankton in Jordan Basin, observed during net hauls. Thus, we might expect there to be significant chalk clearing by zooplankton at that site. The sediment traps (currently being processed) will likely provide the best evidence, for or against this hypothesis. We also opted to put both sediment traps in the patch rather than one inside and one outside the patch as was done in November '01. Putting both traps in the patch insured sufficient material would be collected and provided a check on replication. Moreover, these two traps, along with the two Lagrangian drifters (drogued to different depths), provided a much better idea of the location of the chalk patch as it was sheared at different levels within the water column.



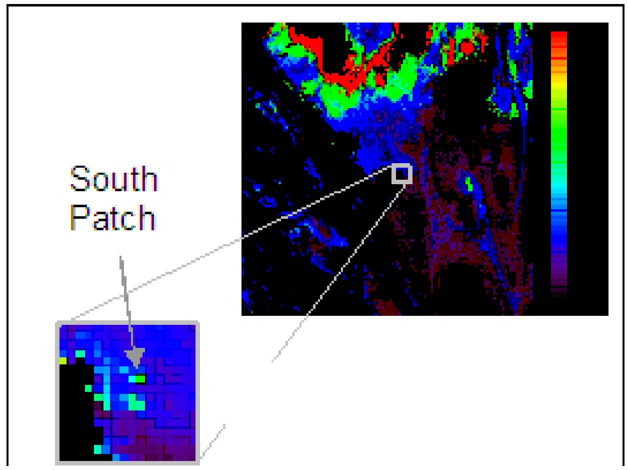


Figure 2. MODIS Aqua images of two patches made during June 2003 cruise, with insets showing fine scale views of patches. Data processed to give calcite concentration (using two-band calcite algorithm described in Gordon et al.(1988)and Balch et al. (1996) ; see color bar to right of each image) A) Jordan Basin Patch, June 13, 2003, 1250h EDT. Patch had three bright lobes with high calcite concentration B) Southern patch June 17, 2003, 1400 EDT. Patch had two bright of lobes with high calcite concentration, to the east of the cloud edge (color-coded here as black). Each pixel was about one square kilometer in area.

IMPACT/APPLICATIONS

These experiments were designed to identify the major loss terms of optically-active particles. This is critical for understanding the evolution of the underwater optical field and prediction of underwater visibility on horizontal and vertical spatial scales of 1-10,000 m and 1-100m, respectively, and time scales of hours to several days. The adsorption of chromophoric DOC onto chalk particles has ramifications to the fate of DOC, the largest organic pool in the sea. Overall, the data demonstrate how important physical mixing conditions are to the initiation and retention of a highly reflective coccolithophore bloom. The potential importance of microzooplankton (relative to macrozooplankton) to loss of the chalk was unexpected and has implications to calcite dissolution and turnover in the sea.

RELATED PROJECTS

Dr. H. Gordon (U. Miami) and W. Balch have collaborated in earlier chalk experiments as part of a NASA MODIS contract to derive a remote sensing algorithm for the determination of $CaCO_3$ from space. During year 1 of this project, the NASA MODIS team funded Balch to do chalk patch studies for calibration/validation of the MODIS suspended calcite algorithm. This work was extremely complimentary to the ONR science (but certainly not overlapping in the objectives). The NASA MODIS contract paid for ship time plus chalk during the November ’01 cruise. A DURIP grant, “Upgrading instrumentation to measure light scattering in the sea” was also funded as part of this project (co-authored by J. Vaughn, [Univ. New England] and Balch; this equipment was utilized in these experiments as well as previous ONR-funded experiments.

REFERENCES

Balch, W.M., Kilpatrick, K., Holligan, P.M., Harbour, D., and Fernandez, E., 1996, The 1991 coccolithophore bloom in the central north Atlantic. II. Relating optics to coccolith concentration: Limnology and Oceanography, v. 41, p. 1684-1696.

Fernández, E., Boyd, P., Holligan, P.M., and Harbour, D.S., 1993, Production of organic and inorganic carbon within a large scale coccolithophore bloom in the northeast Atlantic Ocean: Mar. Ecol. Prog. Ser., v. 97, p. 271-285.

Gordon, H.R., Brown, O.B., Evans, R.H., Brown, J.W., Smith, R.C., Baker, K.S., and Clark, D.K., 1988, A semianalytic radiance model of ocean color: J. Geophys. Res., v. 93, p. 10909-10924.

Knap, A.H., 1993, Bermuda Atlantic time-series study-BATS Method Manual, US JGOFS Plann. And Coord. Off., Woods Hole Oceanogr. Inst., Woods Hole, MA., p. 108.

Knauer, G.A., Martin, J.H., and Bruland, K.W., 1979, Fluxes of particulate carbon, nitrogen and phosphorus in the upper water column of the northeast Pacific: Deep-Sea Research, v. 26, p. 97-108.

PUBLICATIONS

Balch, W. M. Re-evaluating the physiological ecology of coccolithophores. Chapter for: "COCCOLITHOPHORES - FROM MOLECULAR PROCESSES TO GLOBAL IMPACT". Editors: Hans R. Thierstein and Jeremy R. Young. Springer-Verlag Revised June 2003. [in press, refereed]

Broerse, A.T.C., Tyrrell, T., Young, J. R., Poulton, A. J., Merico, A. and W. M. Balch. The cause of bright waters in the Bering Sea in winter. 2003. Continental and Shelf Research [in press, refereed]

Balch, W. M., D. Drapeau, B. Bowler, E. Booth, J. Goes, A. Ashe, and J. Frye. 2003. A multi-year record of optical properties in the Gulf of Maine: I. Spatial and temporal variability. In revision for Progress in Oceanography. [refereed]

Vaillancourt, R.D., C.W. Brown, R.R.L. Guillard, W. M. Balch. 2003. Light backscattering by phytoplankton algae and a heterotrophic bacterium measured with a multi-wavelength, fixed-angle backscattering meter. In revision for J. Plankton Res.. [refereed]

Knobelspiesse, K. D., Pietras, C., Fargion, G.S., Wang, M., R. Frouin, Miller, M. A., Balch, W.M. and G. Cota. 2003. Maritime aerosol optical data collected by the NASA SIMBIOS project. Remote Sensing of the Environment [refereed].

PUBLISHED ABSTRACTS (non-refereed)

Balch, W.M., A.J. Pluddemann, C.H. Pilskaln, H.G. Dam, G.B. McManus and J.I Goes. 2002. Chalk-Ex: An ocean optics manipulation experiment on the fate of calcite particles. AGU Fall Meeting, *EOS Transactions*, 83, No. 47, p. 679.

Dam, H.G., C.H. Pilskaln and A.N. Smith. 2002. Aggregation and downward export of particles during Chalk-Ex 2001. AGU Fall Meeting, *EOS Transactions*, 83, No. 47, p. 680.
Pluddemann, A.J., W.M. Balch and C.H. Pilskaln. 2002. Evolution of stratification and shear during Chalk-Ex 2001. AGU Fall Meeting, *EOS Transactions*, 83, No. 47, p. 680.

Bowler, B., W. M. Balch, D. Drapeau, J. Goes, and E. Booth. 2002. Optical Results From the November '01 "Chalk-Ex" Ocean Optics Manipulation Experiment. Presented at the December '02 AGU Meeting in San Francisco, *EOS Transactions*, 83, No. 47, p. 680.

Goes, J. I., W.M. Balch, B. Bowler, D. Drapeau, E. Booth. 2002. Evidence of DOM removal by Cretaceous CaCO3 particles during Chalk-Ex 2001. Presented at the December '02 AGU Meeting in San Francisco, *EOS Transactions*, 83, No. 47, p. 680.

Balch, W. M., H. Gordon, B. Bowler, D. Drapeau, J. Goes, and E. Booth. 2002. Suspended chalk and ocean optics. Ocean Optics XVI. Santa Fe, NM. Presented November 2002. Sponsored by Office of Naval Research. *Program and Abstracts.* p. 27.

Goes, J. I., W. M. Balch, J. Vaughn. Optical properties of submicron particles in seawater using flow field flow fractionation. Ocean Optics XVI. Presented November 2002. Sponsored by Office of Naval Research. *Program and Abstracts.* P.50.